Residual Densities Affect Growth of Overstory Trees and Planted Douglas-Fir, Western Hemlock, and Western Redcedar: Results from the First Decade

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ABSTRACT

In recent years, interest has increased in silvicultural systems and harvest cuts that retain partial overstories, but there are few data available on the growth of the understory trees in such stands. We studied the response of overstory trees and underplanted seedlings, Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*), to a range of residual overstory densities. Forty to 70-year-old Douglas-fir stands in western Washington were harvested, leaving retention levels of 0, 8, 16, 24, 32, and 40% of full stocking. The 9-year response of the understory seedlings was species-dependent with Douglas-fir the largest in diameter (mean diameter 6.4 cm and mean height 3.8 m), western hemlock the tallest (mean diameter 5.5 cm and mean height 5.4 m), and redcedar the smallest (mean diameter 1.5 cm and mean height 1.5 m), in part because it was heavily browsed. Douglas-fir and western redcedar showed the greatest growth in the lowest retention levels (0 and 8%), and western hemlock responded best at the middle retention levels (8 and 16%).

Keywords: overstory retention, regeneration, *Pseudotsuga menziesii*, *Tsuga heterophylla*, *Thuja plicata*

During the past two decades, interest in two-aged silvicultural systems and harvest cuts that retain partial overstories in dispersed or aggregated patterns has increased because of their reduced visual impact and potential benefits to other forest uses and resources such as plant and wildlife habitat (e.g., Franklin et al. 1997, Curtis et al. 2004). Little, however, is known about the effects of different overstory densities on growth and survival of the overstory component and on the establishment and early development of regeneration in such systems. Much of the information that is applicable to western Washington and Oregon is based on either retrospective studies or is the result of modeling efforts. Relatively few empirical data exist.

The response of even-aged Douglas-fir (*Pseudotsuga menziesii*) stands to different levels of thinning has been long studied, and it is known that greater diameter increment is achieved in stands with reduced levels of competition (Marshall and Curtis 2002). Trees in moderately to heavily thinned stands retain a high ratio of live crown and exhibit rapid crown expansion (Chan et al. 2006). Despite these benefits, concerns remain about the retention of partial overstories in a two-aged system. These concerns include potential logging damage and windthrow losses because residual trees represent substantial economic value and may provide ecological benefits during the recovery period (Rosenvald and Lõhmus 2008). Most wind damage occurs within the first 5–6 years after harvest; however, there is flexibility in thinning levels if consideration is given to topography and previous management regimes (Moore et al. 2003).

Specific information on the growth and development of understory regeneration in two-aged stands under different overstory retention levels is scarce, although some generalities can be stated, particularly for Douglas-fir. Douglas-fir is more shade intolerant than western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*), its two principal conifer associates in coastal Washington and Oregon (Minore 1979). Apparent shade tolerance is not solely a matter of light, but may vary with age and is influenced by temperature, soil moisture, and above- and belowground competition from associated vegetation, all of which are related to site quality and to topographic and geographic location (Kimmins 1987, Klinka et al. 1990, Carter and Klinka 1992). Douglas-fir is capable of establishment and strong development under full overhead light on most sites, yet partial shade can be beneficial and sometimes essential to establishment and early development on hot and dry or frost-prone sites (Isaac 1943, Strothman 1972).

Isaac (1943) stated that Douglas-fir regeneration requires overstory densities of less than 50% of full basal area stocking or openings 0.4 ha or larger in size. Cole and Newton (2009) concluded that establishment of conifers would be negatively affected by residual overstories with a relative density (RD; Curtis 1982) greater than 5.5 (58% of fully stocked). Retrospective assessments of shelterwood cuts and other two-storied stands led Williamson (1973) and

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; hectares (ha): 1 ha = 2.47 ac.

Table 1. Site and stand characteristics before treatment for the three blocks in the overstory density study.

	Block 1	Block 2	Block 3
Latitude	46°56′ N	46°52′ N	46°54′ N
Longitude	123°12′42.84″ W	123°12′46.56″ W	123°7′26.53″ W
Slope (%)	S <2%	0–5	0–15
Aspect	SE	Variable, predominantly S	SE
Elevation (m)	518	198	350
Soil type	Bunker silt loam	Olympic clay loam and Raught silt loam	Olympic silt loam
Initial BA (m^{2}/ha)	49	64	52
Species composition	79% Douglas-fir 18% western hemlock 3% Pacific silver fir	98% Douglas-fir 1% western hemlock <1% red alder <1% western redcedar	91% Douglas-fir 6% western hemlock 2% western redcedar <1% red alder
No. stems/ha	280	277	230
Approximate stand age (yr)	40	70	70
Quadratic mean diameter (cm)	48	53	53
Mean height (m)	29	48	44
Estimated site index (m/50 yr)*	35	39	37
RD (English units)	7.07 (50)	8.80 (59)	7.10 (48)

* From Bruce (1981).

Wampler (1993) to similarly conclude that successful regeneration of Douglas-fir required less than 50% overstory cover. Wampler also found that at lesser levels (i.e., below 50%) of overstory retention, understory height growth decreased with increasing overstory density and the presence of western hemlock in the understory. Some retrospective studies have looked at the question in relation to numbers of residual trees and have concluded that reductions in understory growth rate occur at 12–15 trees/ha (Rose and Muir 1997, Acker et al. 1998). Other studies, through either retrospective assessments or modeling, have predicted losses in understory wood production with five or fewer retained overstory trees (Long and Roberts 1992, Hansen et al. 1995, Zenner et al. 1998). Retrospective studies and modeling, however, require that stand histories and structures be reconstructed or estimated.

Given the scarcity of designed field tests of two-aged silviculture, the USDA Forest Service Pacific Northwest Research Station and Washington State Department of Natural Resources established a cooperative study in 1999 to quantify the effects of different overstory retention levels on both overstory and understory trees (regeneration). The study was established in young-growth Douglas-fir stands typical of those managed and harvested on private and public forestlands in the Douglas-fir region of western Oregon and Washington. Because interest has increased in managing other conifers in both pure and mixed stands and because they may respond differently to overstory retention, the study included understory seedlings of western hemlock and western redcedar as well as Douglas-fir.

Materials and Methods

Site Description

Our experiment was established in predominantly Douglas-fir stands in the Capitol State Forest southwest of Olympia, Washington (Table 1). This is an area of high site quality and relatively high rainfall (150+ cm/year) in which western hemlock also grows well and in which minor to moderate amounts of western redcedar, Pacific silver fir (*Abies amabilis*), red alder (*Alnus rubra*), and bigleaf maple (*Acer macrophyllum*) may also be present. Associated species include salal (*Gaultheria shallon*), sword fern (*Polystichum munitum*), vine maple (*Acer circinatum*), salmonberry (*Rubus spectabilis*), and trailing blackberry (*Rubus ursinus*). The stands range in age from about 40 to about 70 years, with mean tree heights of about 29 to 48 m (Table 1).

Study Design and Establishment

The study was a randomized complete block design with three blocks and six overstory treatments. Treatments were density reductions of the overstory to retain residual stockings of 0, 8, 16, 24, 32, and 40% of "full basal area stocking." "Full stocking" was defined as the basal area for RD 9.5 (65 if English units are used for calculation; Curtis 1982). It was calculated from the quadratic mean diameter (QMD) of all Douglas-fir present in each plot before treatment [rearranging the RD equation, full basal area m^2/ha = $9.5 \times \sqrt{(QMD}$ of Douglas-fir before cut)]. These treatments were selected to provide a range of light levels from full sunlight to about 20% light transmission (based on figures in Smith 1991). The full stocking criterion was used instead of simpler metrics (such as number of trees per ha or basal area) to provide greater applicability to other sites and tree ages. Treatment units were 1.4–1.5 ha with internal measurement plots of 0.37 ha, thus providing 23–30 m buffers. Leave trees were selected based on their spacing and vigor (lack of damage, crown class, and crown ratio). All units were harvested during the early summer of 2000.

Douglas-fir, western hemlock, and western redcedar seedlings were produced at the Webster State Nursery (Olympia, WA). Seedlings were grown for 1 year as container stock, out-planted to a nursery bed, and then lifted after 1 year. Planting at the study blocks occurred in March 2001. A total of 2,250 seedlings were planted in a systematic design of diagonal rows to maximize between-species competition and minimize clumping of species that might result in an increase of error variances. The mixed-species plots each consisted of 125 trees (41–42 of each species) planted at a 3 m × 3 m spacing (1,100 trees/ha), resulting in a plot size of approximately 0.11 ha. Mean heights immediately after planting were 38 cm for Douglas-fir, 46 cm for western redcedar, and 41 cm for western hemlock.

Competing vegetation was controlled to ensure relative similarity in abundance across plots and survival of planted seedlings. Large shrubs and advanced regeneration were removed with hand tools before planting (early 2001). In early 2003 and fall 2006, shrubs and

Table 2. Treatment targets, characteristics of residual trees, and logging damage by block, overstory retention treatment, and species in the overstory density study.

Block	Retention		Douglas-fir			Western hemlock			Logging damage (%)
	Target	Postlogging	dbh (cm)	Height (m)	No./ha	dbh (cm)	Height (m)	No./ha	
	. . . .(%)								
1	8	8.2	41	27	32	63	36	3	30
	16	22.1	50	30	59	44	33	3	22
	24	26.0	48	31	59	55	32	3	17
	32	32.9	48	29	72				16
	40	38.3	48	30	126	49	27	16	27
2	8	8.5	57	39	37	30	16	3	47
	16	17.8	71	52	35				27
	24	26.2	59	46	59				27
	32	34.7	65	49	64	25	22	8	28
	40	41.9	64	51	92				27
3	8	7.5	58	44	22	59	46	3	33
	16	16.4	71	49	25	57	43	5	20
	24	23.0	58	42	64				28
	32	32.2	62	45	64	63	37	3	22
	40	42.3	67	44	89	45	34	3	23

Note that the post-treatment retention level of most plots was close to their targeted level of basal area stocking expressed as a percentage of full stocking (Curtis 1982). Western redcedar was found only within block 3, 24% retention level plot (3 trees/ha, mean dbh 141 cm, and mean height 38 m).

trees (primarily *Acer circinatum* and *Alnus rubra*) that were overtopping planted conifers were cut.

Measurements

Dbh, height to live crown, and total height were measured on all overstory trees within each treatment plot when logging was complete at the end of the 2000 growing season and at the end of the 5th and 10th subsequent growing seasons. Damage codes pertaining to insect and disease presence, form irregularities, and animal, weather, and logging damage were recorded on all trees where applicable. Damage severity was recorded as severe (affecting growth or wood quality) or not. An additional assessment of damages was completed in the winter of 2006–2007 (end of year 6) after a local windstorm.

All seedlings were measured after planting in the spring of 2001 and after the 1st, 2nd, 5th, and 9th growing seasons. A partial measurement was also completed in year 3. The attributes assessed were stem diameter at 15 cm above the ground, total height, and damage. In year 9, diameters of trees taller than 1.3 m were measured at 1.3 m in height instead of at 15 cm. Because understory planting was completed the year after treatment, the 2009 measurement data represented year 9 since out-planting for the seedlings (11 years from seed) and year 10 for the overstory trees (i.e., since harvest of neighboring trees).

Analyses

We assessed treatment effects on seedling survival, size, and damages at different times by analysis of variance and linear regression analysis (PROC GLM and PROC MIXED; SAS Institute, Inc. 1999). Overstory removal was considered a fixed effect, but because treatment levels were spaced in a linear manner, SAS CONTRAST comparisons could be made to assess linear and quadratic responses. Analyses used 17 *df* (3 blocks and 6 treatment levels). Analyses for diameter, height, and volume growth of the overstory were limited to Douglas-fir, which accounted for 95% of the residual stems. Seedling size at year 9 included both trees above and below breast height and necessitated the conversion of dbh data to basal diameter (at 15 cm height) using a regression from trees measured at the two heights on a similar site with a retained overstory at the midpoint of retention levels for this study (20%). Volume of overstory trees was calculated using equations given by Bruce and DeMars (1974).

Results and Discussion

Residual Overstory Trees

Logging Damage

Residual basal area in the treatment plots closely approximated (within 2–6%) target values (Table 2). Damage to residual trees during the removal of the overstory averaged 24% over all plots and ranged from 16 to 47% of the trees in each plot. The highest percentage of damaged trees occurred in the 8% treatment in each block. Although logging damage was widely spread, it was only recorded as severe on 4 trees at all 3 blocks (0.3%). Of the trees coded as receiving some logging damage, 86% consisted of only minor basal bark removal. The next two most common categories of logging damage included minor live branch breakage and minor bark removal on the upper bole.

Wind Damage

Some windthrow was anticipated among the residual trees, but during the first 5 years of the study, such losses were slight. No windthrow occurred in block 1 (the only block previously thinned) and only 3.6 and 0.7% of trees, respectively, were windthrown in blocks 2 and 3. The change in overstory density levels due to windfall during this period was negligible, and the low volume of windfall made salvage of the logs economically unfeasible. On Dec. 14, 2006, a windstorm with gusts of approximately 144 km/hour from the south and southwest caused major damage throughout the region (National Oceanic and Atmospheric Administration 2006, Mass and Dotson 2010). Many trees in our study were blown down, were snapped off directly below the crown, or exhibited an extreme lean and were expected to fall down. The damage was not related to overstory treatment but did differ substantially by block. It was heaviest at block 2, where 25% of the trees were affected in the most damaged treatment (24% of full stocking), and was negligible in block 3.

No damage occurred to trees at block 1, perhaps because the younger trees in this block were shorter and less susceptible. The

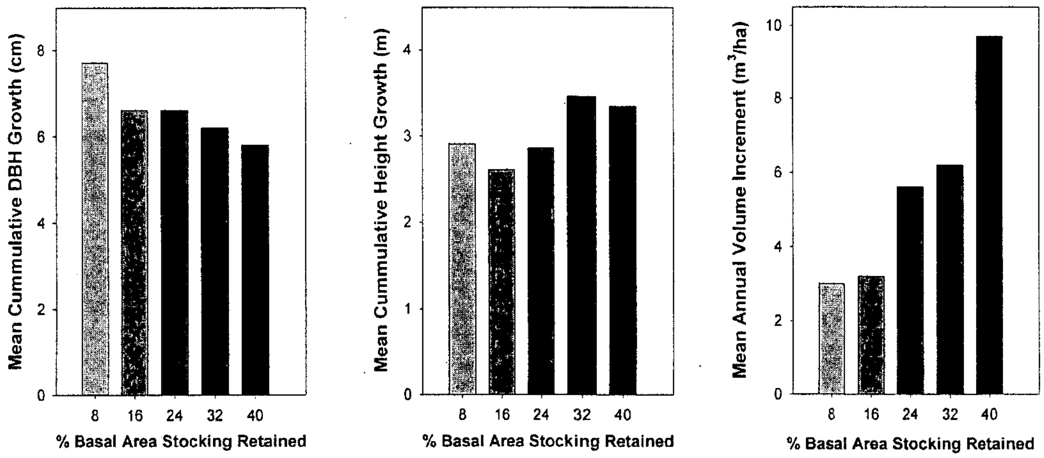

Figure 1. Mean cumulative diameter growth, cumulative height growth, and annual volume increment per ha of overstory Douglas-fir trees in first 10 years since treatment by overstory retention level (given as a percentage of full basal area stocking: RD = 65).

Table 3. Percent mortality of the understory seedlings by time period, species, and retention treatment.

	Years 0–2			Years 3–5			Years 5–9		
Retention	Douglas-fir	Western hemlock	Western redcedar	Douglas-fir	Western hemlock	Western redcedar	Douglas-fir	Western hemlock	Western redcedar
	(%)								
0%	7	17	2	2	5	0	2	0	2
8%	2	11	1	0	2	1	4	2	1
16%	4	18	0	3	3	10	5	3	1
24%	3	7	0	1	0	0	3	1	3
32%	2	7	1	7	7	2	4	0	3
40%	5	2	1	6	2	2	5	0	3

main difference between the 3 blocks, however, is in exposure. An area immediately south of block 2 had been cleared only a few months before the 2006 windstorm. No additional significant wind damage was recorded after the 2006 event. In our related Silvicultural Options for Young-Growth Douglas-Fir Forests study (Curtis et al. 2004), trees in a similar treatment that retained approximately 20% of full basal area stocking (midpoint of retention levels for this study) were not subjected to such high wind gusts in the 4 years between treatment and assessment. During that period, the maximum wind gust recorded at that site was 77 km/hour, and approximately 11% of trees were blown down. Many downed trees were near the border with a cleared unit, and root rot was present in 63% of the affected trees. It, therefore, appears that if some overstory is retained at any level, then consideration needs to be given to topography, soil type, presence of root rot, and both previous and adjacent management regimes (Mitchell and Rodney 2001, Moore et al. 2003). In particular, areas with pretreatment conditions resulting in high height/diameter ratios may be unsuitable for these treatments (Cremer et al. 1982, Schelhass 2008). Wider initial spacing and earlier periodic thinning would probably result in stands with lower height/diameter ratios and reduced susceptibility to windthrow.

Mean Tree Growth

Diameter growth of the overstory Douglas-fir trees between years 0 and 5 was not different among the overstory treatments. Based on previous studies (Marshall and Curtis 2002) and the year 10 results, we suspect that the overstory trees responded to thinning to some degree but did not do so differentially among treatments at this early stage. By year 10, the range of mean diameter growth among treatments had differentiated to a greater extent than in year 5 (P = 0.057; Figure 1). Mean 10-year cumulative dbh growth in the 40% treatment was 5.8 cm compared with 7.8 cm in the 8% treatment. A delay in response to thinning of greater than 10 years is not uncommon for mature trees (Garber et al. 2011), and we expect diameter response to treatment to be greater by year 15 as canopies in the denser stands start to close.

Height growth did not differ significantly by treatment at year 5 or year 10 but did show a trend toward greater growth at the heavier retention levels, particularly at year 10. The number of trees per ha differences between treatments resulted in substantial differences in volume growth per ha (Figure 1).

Understory Trees (Regeneration)

Seedling Mortality

Mortality of all species was generally very low through year 9 (Table 3), averaging 9% overall. The fact that mortality was low even in the densest overstory treatment (40%) is consistent with findings of Isaac (1943), Williamson (1973), and Wampler (1993), indicating that removal of at least 50% of the overstory should be sufficient for survival and early growth of Douglas-fir. Western hemlock sustained the highest mortality rate of any species in the three least-dense treatments during the first 2 years. There was not significant damage coded, browse or otherwise, for western hemlock in these lower density treatments, and except for increased exposure associated with the more open stands, there was no perceptible pattern of block or planting conditions that would account for the higher mortality. The higher mortality of western redcedar in the 16% treatment for years 3–5 was limited to a single block (block 2)

Table 4. Percentage of seedlings damaged by animal browsing recorded by time since planting, species, and overstory retention treatment.

Retention	Year 5 Douglas-fir	Year 5 Western hemlock	Year 5 Western redcedar	Year 9 Douglas-fir	Year 9 Western hemlock	Year 9 Western redcedar
			(%)			
0%	40	10	79	2	2	69
8%	42	11	67	6	0	67
16%	37	10	56	6	1	56
24%	32	3	64	9	1	64
32%	25	5	61	10	0	61
40%	34	7	90	20	4	77

Table 5. Seedling diameter (measured at 15 cm) and height by year since planting, overstory retention treatment, and species.

Retention	Diameter Yr 2	Yr 3	Yr 5	Yr 9	Δ Yr 2–5	Δ Yr 5–9	Height Yr 2	Yr 3	Yr 5	Yr 9	Δ Yr 2–5	Δ Yr 5–9
	(mm)						(cm)					
Douglas-fir												
0%	9.8	14.6	27.8	83.4	18.0	55.0	66.8	86.8	187.8	480.2	121.0	292.4
8%	9.9	15.5	28.5	78.7	18.6	50.2	64.0	88.3	187.3	466.1	123.3	278.8
16%	9.3	13.7	25.0	72.2	15.7	47.2	61.1	83.2	176.6	435.3	115.5	258.7
24%	8.2	11.3	19.9	54.2	11.7	34.3	60.8	75.2	142.7	322.6	81.9	179.9
32%	8.9	—*	21.9	55.3	13.0	33.4	63.9	—*	168.4	341.3	104.5	172.9
40%	7.6	10.2	15.2	39.1	7.6	23.9	62.1	77.2	130.7	236.7	68.6	106.0
Western hemlock												
0%	9.8	14.9	29.5	53.9	19.7	24.4	98.6	138.8	266.1	506.2	167.5	240.1
8%	10.1	16.4	34.2	67.2	24.0	33.0	108.5	155.8	304.5	610.7	196.0	306.2
16%	9.5	15.6	31.7	61.8	22.2	30.1	109.2	157.8	289.8	578.1	180.6	288.3
24%	8.7	13.1	27.0	49.7	18.3	22.7	107.9	144.0	268.0	507.9	160.1	239.9
32%	9.9	—*	32.7	61.4	22.8	28.7	120.8	—*	311.4	588.7	190.6	277.3
40%	7.8	11.3	21.2	37.7	13.4	16.5	105.6	133.1	234.6	429.5	129.0	194.9
Western redcedar												
0%	7.1	9.5	15.1	15.4	8.0	0.3	57.3	56.7	93.7	162.1	36.4	68.4
8%	6.5	9.0	13.7	15.2	7.2	1.5	57.5	59.1	90.3	151.5	32.8	61.2
16%	6.5	9.5	14.0	15.5	7.5	1.7	55.2	59.7	92.7	160.4	37.5	67.7
24%	6.5	8	12.8	15.5	6.3	2.7	58.7	62.6	95.8	166.6	37.2	70.8
32%	6.4	—*	12.8	15.6	6.4	2.8	54.6	—*	95.1	164.3	40.5	69.2
40%	5.7	7.1	9.6	10.5	3.9	0.9	56.7	57.6	80.5	104.8	23.8	24.3

* No data available.

where a large number of seedlings were coded as "missing" rather than "dead" and may be attributable to both heavy browse and competing vegetation, primarily sword fern and trailing blackberry.

Seedling Damage

The two most common types of damage for Douglas-fir through year 5 were browse (35% of all trees) and top-dieback (5%). Western hemlock also were browsed and experienced top-dieback, but experienced them to a substantially lesser degree: only 8% of all trees exhibited browse and <1% had top-dieback. Browse was the only damage recorded for western redcedar at more than an incidental level but was extensive, affecting 76% of all western redcedar trees (92, 60, and 73% at blocks 1, 2, and 3 respectively). For Douglas-fir and western hemlock in year 5, there was more browse damage coded in plots with less retained overstory than those with higher retention levels (Table 4). Increased forage production in the more open treatments may have resulted in greater use by deer and elk (Crouch 1976). By year 9, however, browse damage was reduced overall for Douglas-fir and western hemlock (all blocks and treatments) and was slightly higher in the plots with higher residual stand density, probably due to treatment differences in tree height that had developed by this time: the shorter trees under the higher residual stand densities were more subject to browsing (Table 4). Western redcedar, a species preferred by deer (Martin and Baltzinger 2002), continued to receive extensive browsing and height remained short in all treatments.

Seedling Size and Growth

By year 5, both stem diameter at 15 cm and height were significantly different among species. Western hemlock had the largest diameters and heights followed by Douglas-fir and then western redcedar at all treatment levels (Table 5 and Figure 2). Western hemlock exhibited the greatest growth rates between years 2 and 5 and Douglas-fir between years 5 and 9. Between years 5 and 9, diameter growth of Douglas-fir exceeded that of western hemlock in all treatments, but its height growth exceeded that of western hemlock only in the most open treatment. As a result, Douglas-firs at age 9 were larger in diameter than western hemlocks in nearly all treatments, but western hemlocks remained taller in all treatments. Western redcedar growth was negligible as a result of heavy browse, and the seedlings did not exhibit a significant diameter or height response to treatment during the 9-year measurement period. Trends in Douglas-fir and western hemlock treatment response that were apparent at year 5 were accentuated by year 9 (Figure 2). Douglas-fir diameters exhibited the greatest differentiation between treatments, declining linearly with increased residual density;

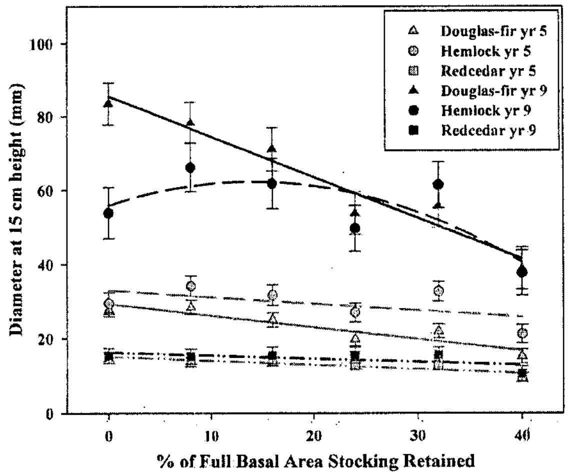

Figure 2. Response of diameter of underplanted species (measured at 15 cm) to increasing levels of overstory retention at 5 and 9 years since planting.

growth of western hemlock exhibited a quadratic response to density, with the best growth occurring between 8 and 16% of full stocking.

For Douglas-fir, stem diameter was significantly different by treatment in all measurement years ($P < 0.05$), but height was not significantly different until year 5 (Table 5). In all years, the Douglas-fir seedlings in more open environments generally grew at a greater rate than those with a higher overstory density. At the last measurement, the two extremes in the range of treatments had differentiated to a great extent: mean percent diameter growth from years 5–9 in the 0% treatment was 2.3 times greater than that in the 40% treatment. Height growth between years 2 and 9 responded similarly.

Western hemlock diameter differed significantly among treatments by year 2. The largest trees, both in height and diameter, occurred not in the clearcut (0% overstory retention) as with Douglas-fir but in the intermediate treatments. The smallest diameters occurred in the densest (40%) treatment. At year 5, western hemlock height was generally greatest in the 8 and 16% treatments and shortest in the densest (40%) treatment and in the clearcut (0%). In year 9, the same growth/treatment patterns were repeated but with greater amplitude.

Analysis of *nondamaged* western redcedar diameter and height growth did not show significant differences among treatments at year 9. Inclusion of the damaged seedlings, however, showed that by year 5, those in the 40% retention level were significantly shorter than those in the more open treatments and did have substantially greater browse damage coded at ages 5 and 9 years than any of the more open treatments.

The response of seedlings in this study was similar to that of understory seedlings in other studies. Two-aged systems on the lighter end of the retention scale not only may perform well in seedling growth but also may help conserve the production of nontimber forest products, forest structure, and processes (Paquette et al. 2006). Maas-Hebner et al. (2005) found that based on size and damage at year 8, the species suitability for underplanting in stands ranging from 72 to 547 trees/ha could be ranked in the following order: western hemlock, Douglas-fir, and western redcedar. Despite the differences in residual stand ages and densities (30–142 trees/ha in our study), the findings of these 2 studies were similar at year 5: the growth of western hemlock exceeded that of Douglas-fir. By year 9, however, the treatment responses in our study had shifted, with the growth of Douglas-fir exceeding that of western hemlock in the three treatments with the least overstory (0–62 trees/). Western redcedar, if left unprotected, was too severely browsed to grow productively in our study environment.

Conclusion

Silvicultural systems that retain partial overstory cover appear to be feasible in Douglas-fir stands west of the Cascades based on survival and growth of the residual overstory and regeneration 10 years after the initial regeneration harvest in our study. Logging damage and mortality losses in the overstory during the first few years were minor. Windthrow observed after a severe (144 km/hour) December 2006 windstorm occurred primarily in one block only. We suspect this area was susceptible because the adjacent stands on the side of prevailing winds had recently been clearcut. It, therefore, does not appear that wind damage will be a major factor limiting the success of these silvicultural systems if consideration is given to windthrow risk at the planning stage.

Variation between responses of individual overstory trees to treatment were small at this early stage, but show a trend toward greater differentiation in the future. Although volume growth per individual tree was similar among treatments because height and diameter responded in an opposite manner to increased residual stand density, there were substantial differences in volume growth per hectare among the overstory retention treatments as a result of the large differences in the number of trees per ha.

Mortality rates of the planted trees have been low overall, even at the 40% retention level, but more research needs to be completed on the interaction between overstory retention level and the damage caused by browsing on western redcedar if it is to be included in these two-aged systems.

Based on the year 9 results, reductions in growth rates of understory Douglas-fir will occur if heavier retention levels are used. Growth reductions can be estimated at 6, 13, 35, 34, and 53% for the 8, 16, 24, 32, and 40% treatments, respectively (from Table 5). Height growth reductions of approximately 30% or greater could be expected for the three densest treatments. Although these reductions in seedling size are significant and it is expected that differentiation of the treatments will increase over time (especially for Douglas-fir as the least shade tolerant species), any of the retention levels included in this study may provide adequate survival and growth depending on management objectives. If, for example, management objectives require greater differentiation of canopy levels for habitat development, then lower growth rates in the understory may be acceptable. The increase in the economic value of the retained overstory (more trees per ha) plus the possible increase in aesthetic, wildlife, and plant habitat values might offset the loss in volume growth of the understory. Inclusion of additional management tools such as control of competing vegetation and subsequent stand entries (i.e., thinning or partial overstory removal) over the course of the rotation may be needed to attain specific goals.

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